

Towards a realistic interpretation of quantum physics providing a physical model of the natural world.

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Abstract

It is stressed the advantage of a realistic interpretation of quantum mechanics providing a physical model of the quantum world. After some critical comments on the most popular interpretations, the difficulties for a model are pointed out and possible solutions proposed. In particular the existence of discrete states, the quantum jumps, the alleged lack of objective properties, measurement theory, the probabilistic character of quantum physics, the wave-particle duality and the Bell inequalities are commented. It is conjectured that an intuitive picture of the quantum world could be obtained compatible with the quantum predictions for actual experiments, although maybe incompatible with alleged predictions for ideal, unrealizable, experiments.

1 The intuitive understanding of quantum mechanics

1.1 Introduction

“Nobody understands quantum mechanics” [13]. This sentence of Feynman summarizes a common belief, certainly paradoxical in view of the relevance and the practical success of quantum theory. For most physicists, interested in applications, understanding is not very relevant if it means getting an

intuitive picture of the microworld. In fact, for them the main purpose of physics is to allow predicting (or interpreting) the results of experiments. Other physicists, including most of the workers in foundations, think that the real problem is that, in the attempt to understand quantum mechanics, we should not use concepts similar to those of classical physics[25], or we should adhere to a kind of “weak” objectivity[8].

In contrast with those opinions, in this article I propose that quantum mechanics is less different from classical physics than usually assumed, and it might be understood in a similar manner. In my view a good understanding of quantum mechanics involves both a realistic interpretation and a clear physical model of the microscopic domain. Finding such a model is however very difficult and the existing interpretations of quantum mechanics do not offer it.

It is common to associate realism with locality, a combination allegedly refuted by Bell’s theorem. Actually realism is a more fundamental, epistemological, requirement whilst locality is a physical condition derived from relativity theory. I shall briefly comment on *local realism* in sections 3 and 5 below.

2 Realism and the need of a physical model of the world

Quantum mechanics is extremely efficient for the prediction of experimental results. In almost one century of the theory no significant violation of a quantum prediction has been shown. Furthermore the agreement with experiments is truly spectacular, reaching sometimes a precision of one part in 10^{10} . In contrast the interpretation of the quantum formalism has been the subject of continuous debate since the very beginning of the theory[37] until today. This paradoxical situation, practical success combined with conceptual difficulties, is something new in science. It is true that previous physical theories have given rise to controversy. However in my view the conflict is more acute in the case of quantum mechanics. An undesirable consequence has been some confusion between science and pseudoscience in the public opinion. At present some alleged consequences of quantum theory, like the uncertainty principle or the impossible separation between object and subject, have transcended the scientific community and are com-

mented in newspapers and popular writings, frequently presenting quantum mechanics as magic. The situation has been originated, to some extent, by quantum physicists themselves, who have sometimes stressed the difficulties of understanding, and even the wonder of that fact. In my opinion the lack of understanding is not wonderful but unfortunate. In any case this state of affairs does not contribute to the popular esteem of true science.

“Any serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves”. With these words begins the celebrated 1935 article by Einstein, Podolsky and Rosen[10]. They express in an insuperable form the programme for a realistic interpretation of a physical theory also providing a model of the natural world. I support it for quantum mechanics and I will attempt convincing the readers that the programme is realizable. I shall not discuss the philosophical question of whether there is an external world, independent of our mind, which is usually called ontological realism. I am rather concerned with *epistemological realism, that is the assumption that science makes assertions about the natural world*, and not only about the results of observations or experiments.

For most people philosophy should rest upon the scientific knowledge. I agree provided we refer to philosophy of nature, but in order to produce science some previous philosophical questions should be answered. For instance, what is science?, or better, what are the criteria to distinguish science from nonscientific knowledge?. In order to answer that question I accept the definition of Karl Popper[27]: A claim is scientific if it may be refuted by observations or experiments. However it is true that rarely an established theory breaks down from a single experiment. As Lakatos[17] has correctly pointed out, well tested theories are protected in the sense that the empirical refutation of a single prediction may be interpreted without rejecting the theory, for instance assuming that the particular model used to analyze the experiment was too coarse. Indeed it is a historical fact that established theories are only abandoned, or better superseded, when there is a new theory in agreement with the former one in its domain of validity, but possessing a wider domain.

Quantum mechanics is today a fully established theory and therefore it is very well protected in the sense of Lakatos. I do not only speak about protection against possible empirical violations. What I want to stress is

that there are a number of assumptions which are unnecessary additions to the theory, and are also protected. In my opinion those assumptions are the cause of the strong difficulties in reaching a realistic physical model of the quantum world, as will be discussed in some detail in section 4 of this paper.

It is a fact that there is no clear physical model behind the quantum formalism. In this respect it is the opposite to general relativity. The latter provides a beautiful physical model: matter produces curvature of spacetime and motion is ruled by that curvature. However the calculational tool (the Riemann geometry) is difficult to manage. In quantum mechanics there is a beautiful and relatively simple formalism, that is equations involving vectors and operators in a Hilbert space. However there is no clear physical model behind. I would say that general relativity has physical beauty, the quantum formalism has mathematical elegance.

The renunciation to physical models in quantum mechanics came as a consequence of frustration, due to the failure of the models proposed during the first quarter of the XX century. This was the case specially after Bohr's atomic model, consisting of point electrons moving in circular orbits around the nucleus. That model, generalized with the inclusion of elliptical orbits, produced some progress in the first few years after 1913. However it was increasingly clear that the model was untenable. In 1926 an alternative model was supported by Schrödinger, with an interpretation of his wave mechanics where the electrons were considered continuous charge distributions. As is well known that model was soon abandoned after the correct criticisms by Bohr, Heisenberg and other people. Independently Heisenberg had proposed a formalism, with the name of quantum mechanics, which explicitly rejected any model. Indeed he supported the view that the absence of a picture was a progress towards a more refined form of scientific knowledge. The success of the new quantum mechanics in the quantitative interpretation of experiments, together with the failure to find a good physical model of the microworld, led to the almost universal acceptance of the current view that models are unnecessary or even misleading.

I do not agree with that wisdom. I support the EPR view[10] that there should be “concepts intended to correspond with the objective reality, by means of which *we picture the reality* to ourselves” (my emphasis). That is any physical theory should contain two ingredients: a *physical model* and a *calculational tool* including the formalism and rules for the connection with the experiments. Quantum mechanics possesses only the latter. The calculational tool is essential because it is required for the comparison of the

theory with experiments. Indeed that comparison is the test for the validity of the theory. However the physical model is necessary in order to give satisfaction to the human being who wants to have a picture of the world. Furthermore the existence of a physical model might open the possibility for new developments or applications of the theory and therefore it is not a mere matter of taste.

3 Critical comments on the interpretations

As said above, Heisenberg quantum mechanics was proposed as an abstract formalism without any physical picture behind. Bohr justified the absence of a model with the “complementary principle”, which establishes incompatibility between causal laws and spacetime description, due to the finite (not zero) value of the quantum of action. On this basis he elaborated the “Copenhagen interpretation” [5]. After Bohr’s proposal several modifications or novel interpretations have appeared. The most relevant papers up to 1983 are reprinted in a book by Wheeler and Zurek [37]. I shall comment briefly on those interpretations in the following.

For the sake of clarity I will illustrate the comments with the celebrated “Schrödinger cat” *gedanken* experiment [33]. As is well known it consists of a box containing a radioactive atom and a cat together with a device that kills the cat, say instantaneously, when the atom decays. I will assume that the atom in the excited state, and the live cat are put inside the box at time t_1 . The question is what may be said about the atom and the cat at times $t > t_1$. In particular, what is the prediction of quantum mechanics for the states of both the cat and the atom when the box is open at time t_2 . Any person with knowledge of the law of radioactive decay, even if it is ignorant of quantum mechanics, would claim that the probability of both the cat being alive and the atom being excited at a time $t \in [t_1, t_2]$ is

$$P(t) = \exp[-\lambda(t - t_1)], \quad (1)$$

λ^{-1} being the mean lifetime of the atom. In particular the probability at the moment of opening the box will be $P(t_2)$, eq.(1). In contrast with this response, the answer of an educated quantum physicist will depend on the interpretation which she/he supports, as I comment in the following.

3.1 Copenhagen

According to Bohr's Copenhagen interpretation (CI) the referent of quantum mechanics is not the material world, but the experiments. That is, we should not make assertions about the bodies, but only about the results of possible experiments. Thus a sentence like "the probability that the atom is in the excited state at time t is given by eq.(1)" is considered meaningless. A meaningful assertion should be something like "if we performed a measurement of the state of the atom at time t , the probability that we got the result 'excited' would be given by eq.(1)". The CI is therefore a pragmatic (instrumentalistic) approach which might be called a protocol for the use of the quantum formalism in the analysis of experiments. It is true that Bohr elaborated also an interpretation resting upon the "complementarity" and the "correspondence" principles[5]. But the CI rules for the use of quantum mechanics are to some extent independent on that, and here I will comment only on those rules. CI assumes (or at least it does not reject the assumption) that macroscopic bodies have objective properties (that is independent of any measurement) and its evolution is ruled by the laws of classical physics. Thus it is meaningful to say that a cat is either alive or dead at any time. A more difficult question is whether we are allowed to assign a probability to every one of these possibilities, which I shall answer in the following.

The result of applying quantum mechanics, with the CI rules, to the "cat experiment" is that for $t \in (t_1, t_2)$ the atomic state should be represented by the state vector

$$\begin{aligned} |\psi(t)\rangle &= c_g(t) |g\rangle + c_e(t) |e\rangle, \\ c_e(t) &= \sqrt{\exp(-\lambda(t-t_0))}, c_g(t) = \sqrt{1 - \exp(-\lambda(t-t_0))}. \end{aligned} \quad (2)$$

Now CI offers two possibilities depending on what is supposed to be a measurement. 1) If we assume that the actual measurement takes place at the opening of the box, then quantum mechanics says nothing about the atom and the cat for times $t < t_2$. At time t_2 it predicts that the probability of both the cat being alive and the atom being excited is given by the modulus square of the amplitude $c_g(t)$, eq.(2), which precisely agrees with the naive prediction $P(t_2)$, eq.(1). 2) We might assume that, the cat being a macroscopic system, it may act as a measuring device. In this case, CI tells us that, for any time $t \in (t_1, t_2)$, the probability of both the cat being alive and the atom excited is eq.(1). The latter interpretation (the cat as a measuring device) is consistent with the fact that, if the cat is found dead at time t_2 , a

careful study of the corpse (involving macroscopic manipulations) might determine the time of death, say t_d . This would allow reconstructing the whole history: The cat was alive and the atom excited until t_d . We must assume that, if a similar experiment is performed many times, the distribution of times t_d would converge to an agreement with the probability eq.(1).

It is interesting to study the CI approach to the problem of the “statevector (or wavefunction) collapse”. This is the discontinuous change of the statevector when a measurement is made, e. g. the change from eq.(2) to $|\psi\rangle = |g\rangle$, at the time of opening the box. In our example we may naively believe that the collapse is just a change of our information as a result of the measurement. However the CI is rather cautious on the question and it does neither support nor reject that assumption. CI assumes that eq.(2) is just a mathematical tool for the calculation (of the probabilities) of the results of the experiment, and only for that purpose. Thus the collapse is a mere change to a more convenient mathematical representation.

CI is very good from the practical point of view and avoids any bizarre assumption (which is not the case in more elaborated interpretations commented below.) The problem with the CI is that it creates what has been called “the infamous boundary”[38], that is a sharp discontinuity between micro and macrophysics. The former should be treated with quantum mechanics, the latter with classical physics. In order to remove the boundary and get an interpretation where quantum mechanics is valid also for macroscopic systems, John von Neumann[35] introduced a theory of measurement and even he gave a model of it. That approach has been also named Copenhagen interpretation, which is misleading. For short I shall label it MCI with M standing for modified or measurement. MCI has been supported in most papers and books of quantum mechanics until about 1980.

3.2 John von Neumann

In MCI both the cat and the atom should be treated as quantum objects. Therefore eq.(2) is no longer appropriate and we should represent the state of the whole system, atom plus cat, by

$$|\psi(t)\rangle = c_g(t) |g\rangle |deadcat\rangle + c_e(t) |e\rangle |livecat\rangle. \quad (3)$$

Of course one may object that a dead cat does not correspond to a pure state to be represented by $|deadcat\rangle$. Indeed there are very many pure quantum

states corresponding to a dead cat and similarly for a living cat. However this is not a real problem because MCI assumes that any physical system is associated to a well defined statevector, even if we do not know what it is.

Eq.(3) represents a typical “entangled state”, a name introduced by Schrödinger in 1935[33], who also stated that entanglement is the characteristic trait of quantum mechanics. If CI had been modified with the assumption that statevectors actually represent statistical ensembles this would have lead to the ensemble interpretation, to be commented below. However the mainstream of the scientific community rejected it and supported the “completeness” of quantum mechanics, in the sense that *the statevector represents the actual state of an individual physical system, as opposed to a statistical ensemble*. This assumption makes MCI a bizarre interpretation, which is the point that Schrödinger[33] attempted to stress with his cat paradox. Indeed for many people it is impossible to understand the meaning of a state represented by a superposition of alive and dead cat. Is it something intermediate between life and death? Of course the problem disappears in an ensemble interpretation, that is assuming that eq.(3) just represents our information, $|c_g(t)|^2$ and $|c_e(t)|^2$ being probabilities of live and dead cat, respectively. Thus an ensemble interpretation of eq.(3) seems compelling.

There is also another difficulty for MCI which affects its consistency, namely the problem of the *objectification or individuation*[?]. That is the fact that a particular value is obtained in the measurement amongst several possible values, something not predicted by the formalism. This fact forces us to change the statevector at the time of measurement, a change usually called the “statevector collapse” as mentioned above. In the (instrumentalistic) CI this was just a change of the mathematical representation needed for the analysis of the experiment. However in MCI it becomes a real physical change because it is assumed that the statevector corresponds to an individual system (rather than a statistical ensemble). The problem lies in the fact that the collapse contradicts the Schrödinger equation. Thus the theory of measurement actually departs, and even contradicts, the standard quantum evolution. In order to solve the problem London and Bauer[19] and Wigner[39] suggested that the objectification might take place in the mind of a human observer. This solution dislikes many people. In particular in the cat experiment, it is as if the cat really dies when we look at the box after opening it, or even when we are informed by another people of the result of the experiment (this leads to the “Wigner’s friend” paradox.) Thus the objectification problem in MCI led to postulate a theory of measurement,

which is not a good solution as will be commented in the next section. The consequence of this difficulty has been the replacement of MCI by the many-worlds interpretation (MWI) as the most popular interpretation in recent times.

3.3 Many-worlds

MWI offers a radical solution to the objectification problem, it assumes that objectification never takes place. That is, the evolution is always ruled by the Schrödinger equation for an isolated system. Now no system involving a macroscopic body may be completely isolated, so that in the study of its evolution we should consider the wavevector of the whole universe. In particular, in the cat experiment we should include, in addition to the atom and the cat, also the box, the human observer and everything else. Thus eq.(3) should be replaced by

$$\begin{aligned} | \psi(t) \rangle = & c_g(t) | g \rangle | deadcat \rangle | world - g \rangle \\ & + c_e(t) | e \rangle | livecat \rangle | world - e \rangle, \end{aligned} \quad (4)$$

where $| world - g \rangle$ represents the rest of the world associated to the atom in the ground state and the cat dead, and similarly for $| world - e \rangle$. Eq.(4) seems to tell that there are two copies of the human observer and of the whole world. In the latter copy the observer sees the cat alive and the atom excited, in the former she/he sees the cat dead and the atom in the ground state.

MWI is the unavoidable end of the logical path if we believe that quantum mechanics is universally valid. It was initially proposed by Everett[12] with the name of “relative states interpretation” and elaborated later by de Witt[?], who introduced the name “many worlds”. The aims of MWI are: 1) retain the unrestricted validity of the quantum formalism, 2) remove the need of the statevector collapse, 3) remove the need of an external observer, and 4) derive the Born rule[20]. The latter is the rule for finding the probabilities of the different possible outcomes as a result of a measurement.

Apart from the difficulty of understanding the real meaning of “multiplicity of worlds”, the main problem of MWI is to reproduce the Born rule, that is the quantum prediction for the probabilities of the outcomes in the experiments, without introducing any explicit probabilistic postulate. The standard approach to do that is the theory of decoherence. Decoherence is

the evolution predicted by quantum mechanics when a system possesses very many degrees of freedom, as is the case for a measuring device in contact with the environment. It involves a loss of coherence which leads from a statevector (representing a pure quantum state) to a density matrix, due to the interaction with the environment. That density matrix is approximately diagonal in an appropriate basis (the preferred basis), so that it looks like a probability distribution defined on a set of pure states, as is exhibited in the example eq.(5) below. In the context of MWI the density matrix may be seen as coming from taking the partial trace over those degrees of freedom which are not of interest. For instance if we take the partial trace, with respect to the world states, of the (idempotent) density matrix associated to the statevector eq.(4) we get, taking into account that the statevectors $|world - g\rangle$ and $|world - e\rangle$ are orthogonal to a very good approximation,

$$Tr_{cat} |\psi\rangle\langle\psi| \simeq |c_g(t)|^2 |g - d\rangle\langle g - d| + |c_e(t)|^2 |e - l\rangle\langle e - l|, \quad (5)$$

where $|g - d\rangle$ is short for $|g\rangle |deadcat\rangle$ and $|e - l\rangle$ for $|e\rangle |livecat\rangle$. Eq.(5) is mathematically identical to the representation of the quantum state of the atom plus the cat, which we should use when we do not know its actual state, and consequently we attribute the probability $|c_g(t)|^2$ to the atom being in the ground state and the cat dead, and $|c_e(t)|^2$ the probability of the alternative. The question, to be discussed below, is whether eq.(5) actually corresponds to a mixture or not.

Actually decoherence theory is more involved than it may appear in our example. Firstly we should consider very many terms in the sum which represents the quantum state of the world, rather than only two as in our simplified example eq.(4). Also there is an ambiguity in the world statevector because, it being a linear combination of (tensor) products of statevector, it could be written in many different forms depending on the choice of basis in the Hilbert space. This leads to the problem of the preferred basis, whose solution is one of the achievements of decoherence theory. I shall not discuss here in more detail the different approaches and the technical issues of the MWI and decoherence, and refer to the vast literature on the subject (see e. g.[20] and references therein).

MWI has the virtue that it makes quantum mechanics a selfconsistent theory resting upon a simple postulate: the universal validity of quantum mechanics. Thus it is superior to the old-fashioned CI and MCI. However I disagree with most of the supporters of MWI as to how we should understand

it. For the sake of clarity I will consider a measurement with reference to eq.(5), although now “cat” means the macroscopic measuring device able to suffer an irreversible evolution. Once MWI plus decoherence theory leads us to a reduced density matrix like eq.(5) I propose interpreting it as really representing a mixture, $|c_g(t)|^2$ and $|c_e(t)|$ being probabilities in the usual sense of mathematical measures of our information. Of course this interpretation is not compatible with the assumption that quantum mechanics is complete. That is, the hypothesis that eq.(5) represents a mixture is not compatible with the assumption that the statevector of the world corresponds to an individual world, rather than a statistical ensemble. However it is irrelevant in practice whether we assume that the world statevector represents complete or incomplete information. In fact a *detailed knowledge* of that statevector would always lie beyond the human capabilities. Therefore the assumption that eq.(5) represents a mixture, and quantum mechanics is incomplete, is in my view the most plausible.

In contrast, the conjunction of assuming universal validity (i. e. MWI) and completeness of quantum mechanics leads to the extravagant view that there are many parallel worlds[20]. I believe that this belief is unnecessary. Actually the view rests on what has been termed a *Platonic paradigm* by M. Tegmark[34], who defines it as follows: “The outside view (the mathematical structure) is physically real, and the inside view and all the human language we use to describe it is purely a useful approximation for describing our subjective perceptions.” Of course the mathematical structure referred to by Tegmark is the formalism of quantum mechanics. Thus the Platonic paradigm consists of assuming that standard quantum mechanics is the absolute truth and everything else are shadows.

In my opinion scientific theories, quantum mechanics in particular, are something more modest. They are attempts at describing, rather imperfectly, “the objective reality, which is independent of any theory”[10]. In consequence I prefer to retain as much as possible of the MWI, superior in my opinion to CI or MCI, but without adhering to the Platonic paradigm. The choice is obvious to me: we should reject the completeness of quantum mechanics, that rejection leading to the ensemble interpretation to be commented below.

An interesting consequence of the MWI is that a statevector is only appropriate for the whole world. In contrast, the states of the systems which we may actually study (subsystems of the world) should be generally represented by density matrices. This leads me to *conjecture that only a subset of the*

whole set of possible density matrices represent physical states. This conjecture strongly limits the validity of the superposition principle and gives rise to the problem of determining what is the subset of the whole set of density matrices which correspond to physical (realizable) states. An elaboration of that conjecture will be considered elsewhere.

3.4 Ensemble interpretation

We have seen that in CI and MCI, above commented, it is necessary to introduce a probabilistic postulate, independent of the formalism and the (Schrödinger) evolution equation. That postulate provides the rule for the probabilities of the different possible results of a measurement and the corresponding statevector collapse (Born's rule). In MWI it is controversial whether a probabilistic postulate is introduced. Many authors consider that this is not the case, that the quantum probabilities may be got from the formalism. Actually Everett introduced, in his original formulation, a measure given by the squares of the amplitudes in the sum (of normalized statevectors) which the world statevector consists of. In our example, eq.(4), that measure may allow to assume that $|c_g(t)|^2$ and $|c_e(t)|^2$ are probabilities. Therefore it is my opinion that MWI does introduce a probabilistic postulate, even if it is most natural, as Everett emphasized[12].

I believe that the most plausible assumption is to attribute the quantum probabilities to the fact that any statevector or density matrix represents our (usually partial) knowledge about the actual state of a system, which amounts to assuming that quantum mechanics is incomplete. This is the ensemble interpretation (EI) supported by Einstein[10], [11], and also by some authors in recent times [1]. The assertion seems to me obvious, but it is not easily accepted by the community, because there is a tradition of strong opposition to an ensemble interpretation, which goes back to Bohr. Indeed the well known debate between Bohr and Einstein around 1930[37] had the alternative completeness vs. incompleteness of quantum mechanics as the main theme, and the current wisdom is that Bohr won the debate. Also EI presents a difficult question: What is the ensemble and what is the probability distribution on the ensemble?. I believe that the difficulty to solve this problem is what has inclined people to deny its existence by assuming that quantum mechanics is complete. Thus very few people dare to defend that quantum mechanics may be incomplete. But I support this position and will give arguments for that in the rest of the present subsection.

There is a common objection to the ensemble interpretation, that is the assertion that it would prevent interference. That argument rests upon a naive view of the EI, namely the assumption that in all linear combinations appearing in the application of quantum mechanics, the coefficients squared should be considered as probabilities. Actually the relevant assumption is that statevectors (or better density matrices) represent statistical ensembles rather than individual systems in general. But I should stress that “in general” does not mean always, it means sometimes. In particular when we represent the state of a small system by a linear combination of statevectors it is most common that the linear combination is radically different from a mixture of the states.

3.5 Sketch of a picture of the quantum world

In this paper I shall not consider the quantization of gravity. I understand that this is a shortcoming, but my methodological choice is to try to understand quantum mechanics in the context of the four-dimensional spacetime of (classical) general relativity. I believe that only after having a good understanding of that restricted theory we might try to understand quantum gravity. A realistic approach to quantum mechanics should offer a picture of the world, which I propose to be as follows. In spacetime there are fields, that is something whose nature we do not know but which give rise to phenomena which may be observed. I assume that, even if the state of the world might be represented by some statevector which obviously we cannot know, we must be able to study small systems within the universe, like an atom or a few atoms.

It is not plausible to assume that a small system may be fully isolated from the rest of the world, due to the fact that the vacuum fields propagate so giving rise to an effective interaction of any system with many other systems. But in order to be able to make physics we should assume that microscopic systems, even if not isolated, may be treated with a formalism which in some form takes into account the interaction. That formalism is quantum mechanics. For instance, if we represent the state of an atom by the statevector eq.(2) it is plausible to assume that this representation corresponds to the atom “dressed” by all fields which interact with it. As is well known in quantum electrodynamics the physical electrons are never “bare” but “dressed by virtual photons and electron-positron pairs”. The word “virtual” is just a name for something which we do not know but it has some

observable effects. The point is that the simple representation eq.(2) takes into account the (approximate) action of the vacuum fields, as is shown by the use of the physical, rather than bare, mass and charge of the particles. Thus it is my opinion that to pretend that a statevector represents faithfully the *actual state of an individual system* is a rather presumptuous attitude. It is more plausible to assume that the statevector represents the relevant information available about the system. In summary it is most plausible that the quantum-mechanical representation of a system is always incomplete. In my opinion this incompleteness is the cause of the well known fact that the atom decays at a time which cannot be predicted: The decay is induced by the (random) fluctuations of the vacuum fields. In summary I am convinced that *the complexity of even the most elementary quantum system like a “dressed electron” makes the ensemble interpretation of the statevector the most plausible one.*

3.6 Hidden variables

If we accept the EI the obvious question is: in view that the information provided by quantum mechanics is incomplete, should we attempt to get additional information?. We could say *yes*, searching for a subquantum level may be possible and interesting because that would increase our understanding of the world and might give rise to useful applications. That research is usually known as the *hidden variables programme*. But the answer may be *not*, because the experience shows that the programme has failed in spite of the effort of some (few certainly) people during almost one century. In any case it is my opinion that the rejection of the hidden variables programme is not a sober attitude.

It is a historical fact that the mainstream of the scientific community has been positioned against hidden variables (HV) since the early days of quantum mechanics. Possibly the origin of this fact lies in the strong personality of Bohr combined with the confort produced by the belief that one possesses the final theoretical framework of physics, that is quantum mechanics. With the time the rejection to HV theories was reinforced by the failure to find a useful one. In any case a strong influence had the celebrated von Neumann’s 1932 theorem against hidden variables[?], which prevented the research on the subject during more than three decades. In 1965 Bell[3] showed that the physical assumptions of von Neumann were too restrictive and that (contextual) hidden variables are possible. Indeed for any experiment it is a simple

matter to find a specific contextual hidden variables theory[30]. What is difficult is to get a HV theory valid for the whole of quantum phenomena.

A current wisdom is that HV theories have been proposed with the aim of explaining the probabilistic character of quantum mechanics. It is true that HV theories are always associated to an ensemble interpretation of the statevectors (or the density matrices), but the relevance of HV theories lies in the possibility that they provide a physical model of the world, which in my view is the ultimate goal of any realistic theory. Quantum mechanics does not provide that model, for instance it does not tell us whether electrons are waves or particles, it just says how the electrons behave in specific cases. Thus a HV theory could bring us closer to realism than standard quantum mechanics.

3.7 Kinds of hidden variables

A necessary condition for realism may be stated as follows. Let us assume that in some experiment we want to measure the observable A , which may have several values. Thus the value obtained in a measurement, say a , will depend on the state, say λ , of the system and the observable which we measure. We may write

$$a = a(\lambda, context(A)). \quad (6)$$

where we may interpret λ as the set of values of the (maybe hidden) variables which faithfully determine the state of the system. The dependence on *context*(A) takes into account that the result of the measurement may depend on the full experimental equipment used for the measurement of the observable A . For some people eq.(6) should be called condition for determinism, rather than realism, because the states of the system and the context completely *determine* the result of the measurement[15]. That is, eq.(6) excludes the possibility that natural laws are not strictly causal. In order to met this objection I may replace eq.(6) by the more general one

$$\Pr(a) = P_a(\lambda, context(A)), \quad (7)$$

with the meaning that the states of system and context only determine the probability of getting the value a . Thus eq.(7) is compatible with both the assumption that natural laws are not strictly causal and with its denial. We see that realism (whose necessary condition is eq.(7)) is more general than determinism (or deterministic realism, whose necessary condition is eq.(6).)

The above construction allows defining two possible kinds of hidden variables theories. In fact let us assume that we measure not one but two observables, A and B , in the same experiment. Thus eq.(7) leads to the following expectation value for the product of the two observables

$$\langle AB \rangle = \int \rho(\lambda) d\lambda \sum_a a P_a(\lambda, \text{context}(A, B)) \sum_b b P_b(\lambda, \text{context}(A, B)), \quad (8)$$

where I have assumed one continuous hidden variable with probability density $\rho(\lambda)$. As above the dependence on $\text{context}(A, B)$ takes into account that the results of the measurement might depend on the full experimental context of the measurement. In other words, we do not exclude that the expectation of the product of two observables, $\langle AB \rangle$, measured with a different equipment may lead to a different numerical value. With an assumption as general as eq.(8) it is not strange that, with an appropriate choice of the functions $P_a(\lambda, \text{context}(A, B))$ and $P_b(\lambda, \text{context}(A, B))$, we may reproduce any desired result for $\langle AB \rangle$, in particular a result in agreement with the quantum prediction. HV theories where expectations are given by eq.(8) (or its generalization for more than two observables) are usually named *contextual*, but a more appropriate name would be *general* HV theories. They are obviously compatible with quantum mechanics. These HV theories, being so general, are not too interesting. A restricted family of HV theories consists of those *non-contextual*, where the value of the observable A does not depend on the whole experimental context but only on the state of the system under study, and similar for B . In non-contextual HV theories eq.(8) is replaced by

$$\langle AB \rangle = \int \rho(\lambda) d\lambda \sum_a a P_a(\lambda, A) \sum_b b P_b(\lambda, B). \quad (9)$$

We might say that non-contextual theories assume that bodies possess properties independent of any measurement (such properties, represented by λ , are not the observable properties, but fully determine them.)

Non-contextual HV theories are not compatible with quantum mechanics, a statement known as Kochen-Specker theorem. A proof goes as follows. We consider four dichotomic observables A_1, B_1, A_2, B_2 , that is observables which may take only the values ± 1 . Calculating the expectations via eq.(9) and making use of the properties of probabilities (i. e. $0 \leq P \leq 1$) it is possible to derive the inequality

$$|\langle A_1 B_1 \rangle + \langle A_2 B_1 \rangle + \langle A_2 B_2 \rangle - \langle A_1 B_2 \rangle| \leq 2, \quad (10)$$

which is the most popular form of a Bell inequality[7]. Eq.(10) is violated by the quantum predictions in some cases, which ends the proof. It has been also violated by experiments, as will be discussed in more detail in the section 4.

John Bell[2] introduced local *HV* theories, which are partially non-contextual. Indeed these theories are non-contextual only for measurements performed at spacelike separation, in the sense of relativity theory. This implies that the expectation values of the products should be calculated via eq.(9) when the measurements of *A* and *B* are performed at spacelike separation and via eq.(8) else. Spacelike separation is a rather stringent condition. If the measurement of *A* takes a time between *t* and *t* + Δt_a and that of *B* between *t* and *t* + Δt_b , all times defined in an appropriate inertial frame, then spacelike separation requires that

$$\max\{\Delta t_a, \Delta t_b\} < d,$$

d being the minimal distance between the two measuring equipments (*d* defined in the same frame). Local theories are incompatible with quantum mechanics, which is known as Bell's theorem. The proof is quite similar to the one for non-contextual theories, with the additional condition that the four measurements involved in eq.(10) are performed at spacelike separation. The question whether local HV theories are compatible with experiments is still open, as will be discussed in detail in section 5.

In summary there are three interesting kinds of HV theories fulfilling the following relations of inclusion

$$general \supset local \supset non - contextual.$$

The former (latter) are compatible (incompatible) with quantum mechanics and with experiments. Local theories are incompatible with standard quantum mechanics but it is unknown whether they are compatible with experiments. (Standard means the current use, maybe incorrect, of the quantum formalism, as will be explained in more detail in section 5).

4 Difficulties to reach a physical model of the quantum world

The difficulties for understanding the most strange features of quantum mechanics have led to some proposals to change the theory. For instance an

attempt at solving the problem of objectification has been to add small non-linear terms to the Schrödinger equation. The history of these attempts shows that it is extremely difficult, if not impossible, to modify the quantum formalism without destroying the agreement with experiments. Thus it is sober to believe that quantum mechanics is valid without any modification. A different question is whether it is universally valid, for instance if it remains valid in strong gravitational fields. The common wisdom is that it is, which has lead to the search for methods to quantize gravity, but I will not discuss this question further.

However, as said above, there are many assumptions which are not essential for quantum theory and nevertheless they prevent reaching a physical model of the microworld. In this section those unnecessary assumptions are analyzed and appropriate alternatives proposed. The most relevant of those assumptions are: 1) the alleged need of fundamentally probabilistic, not fully causal, laws in nature, 2) the belief that bodies do not have objective properties, 3) the belief in the dual nature, wave and particle, of every quantum entity, 4) the assumption that physical systems may possess only a discrete set of energies.

4.1 Discrete energy states

As is well known the assumption that systems may possess only energies belonging to a discrete set was the first quantum hypothesis introduced, by Planck in 1900. It was reinforced by the Einstein 1905 proposal of the photon and fully accepted in practice after Bohr's 1913 atomic model. However the quantum discontinuities give rise to difficulties for an intuitive understanding of quantum physics. Hints will be provided here for the solution of these difficulties. Before doing that we should answer two questions: firstly whether the quantum discontinuities are unavoidable and secondly whether they are correctly understood.

In order to answer the first question it is necessary to distinguish the discreteness of the energies in the electromagnetic radiation (the assumption that light consists of particles called photons) from the discreteness of the energies of many body systems like atoms, molecules or nuclei. In the former case there is no need to assume a real discontinuity. Light consists of pure waves[18], but the radiation energy is fluctuating. In an atomic emission the energy is concentrated in wavepackets of the form of needles of radiation, superimposed to a random background, a model which I have discussed more

deeply elsewhere[23] and will not be discussed further here. In contrast the empirical evidence is difficult to reconcile with continuous energies in the case of atoms. Thus the existence of sharp spectral lines or the strong bumps of the cross section in the Franck-Hertz experiment. Of course it is appropriate to point out that, strictly speaking, the possible atomic energies form a continuum, although most of the probability is concentrated near some discrete values. Indeed spectral lines have a finite linewidth as a consequence of the radiative corrections of quantum electrodynamics. This solves one of the apparent paradoxes in the emission (or absorption) of light when it is presented at an elementary level. Indeed it is contradictory to assume that atomic transitions are instantaneous and that the emitted light has a sharp frequency. The fact is that the transition has a duration, Δt , and the emitted light has a finite linewidth, $\Delta\omega$, fulfilling the inequality

$$\Delta\omega\Delta t \gtrsim 2\pi, \quad (11)$$

as is expected in any wave theory.

Similar arguments may be used in order to understand the quantization of angular momentum, as shown for instance in the Stern-Gerlach experiment. In popular expositions the experimental results are presented as if all atoms arrive at one of two sharp points in a screen. Then it is difficult to reach a picture of what is taking place in the interaction between the atom and the inhomogeneous magnetic field. However the truth is that what appears in the screen are two wide spots. It is the case that an accurate quantum mechanical treatment of the experiment precisely predicts that[22].

The examples considered lead us to emphasize a point which is crucial for the attempt of reaching a picture of the quantum world. *The difficulties for an intuitive interpretation may not belong to the real quantum predictions, but to excessive idealizations in popular presentations.* Indeed in textbooks it is usually assumed that making idealizations, and attributing to accidental errors any deviations from the idealized result, contributes to the clarity. It is true that this procedure may simplify the teaching of how to use quantum mechanics, but certainly puts a strong obstacle for getting an intuitive picture of the quantum world. A more detailed discussion is provided in the next section of this paper.

We have seen that, with due cautions, the discreteness of atomic states does not present special difficulties by itself. However there are strong difficulties with some of its alleged consequences, like the quantum jumps discussed in the following.

4.2 Quantum jumps

In the transitions between atomic energy levels there are features which look as counterintuitive. Besides from the common assumption that the transition is instantaneous, wrong as I have discussed above, it is difficult to understand why they happen at random times which cannot be predicted.

Atomic transitions are typical examples of quantum jumps. A lot of discussion exists in the literature about the subject which will not be quoted here. The first thing to stress is that quantum mechanics (the Schrödinger equation) does not predict any jump. The evolution is always continuous. For instance if we have an atom in the ground state and a monochromatic light beam with appropriate frequency impinges it, the composite system atom plus light evolves in a form which may be represented schematically as follows

$$|\phi_{in}\rangle|g\rangle \rightarrow c_g(t)|\phi_g(t)\rangle|g\rangle + c_e(t)|\phi_e(t)\rangle|e\rangle \rightarrow |\phi_{out}\rangle|e\rangle, \quad (12)$$

where $|g\rangle$ ($|e\rangle$) stands for ground (excited) state of the atom and $|\phi_j(t)\rangle$ is the (normalized) state vector of light at time t , $c_g(t)$ and $c_e(t)$ being numerical (possibly complex) coefficients such that $|c_e(t)|$ increases (say from the value 0 at time $t = 0$) whilst $|c_g(t)|$ decreases, but always fulfilling $|c_g(t)|^2 + |c_e(t)|^2 = 1$. Similar considerations apply to the emission of radiation (see eq.(2)).

Answering the questions above posed, we may conclude that the absorption process is not instantaneous, it takes the time involved in the passage from $c_g = 0$ to $c_g = 1$. A similar thing happens in the spontaneous emission and consequently we should not speak about any sharp time of decay. However the decay time may be very short in comparison with the lifetime of the excited state. This is the case with alpha radioactivity, involving lifetimes of order million years to be compared with durations of the decay of fractions of a second. Then, how to explain the well known observation that radioactive atoms decay at random times, as shown by counts in the detector?. As mentioned in the previous section the explanation may be that spontaneous emission is actually induced by the fluctuations of vacuum fields, which I have discussed in detail elsewhere[23]

In MCI the standard answer is that quantum mechanics always predicts a continuous evolution of microscopic systems, whilst the probabilities appear in the act of measurement. This alleviates a problem (quantum jumps look less strange) but create another one: The fact that there are two radically different forms of evolution, namely when *we do not observe* a system its

evolution is continuous, *when we observe* the system there are jumps. Thus we clash with one of the most discussed items in quantum mechanics: the theory of measurement. But before commenting on it, a discussion is convenient about the more general problem posed in the title of the following subsection.

4.3 Do bodies possess objective properties?.

In classical physics, and in any other branch of science except quantum mechanics, it is an implicit hypothesis that any observation or measurement just reveals (removes a veil) a property which exists objectively with independence of any observation. In quantum mechanics this seems to be untrue. Let us clarify the motivation for that belief with an example. We consider a physical system possessing 3 properties corresponding to the observables A , B and C , associated via the quantum formalism to 3 self-adjoint operators in a Hilbert space. As usual I will represent the physical observables and the operators by the same letter. (Incidentally, it is unfortunate to give the same name, observable, to a physical property and to a mathematical element, like an operator in a Hilbert space. This only produces confusion between mathematics and the real world.)

We will assume that both operators A and B commute with C , but they do not commute amongst themselves, that is

$$[A, C] = [B, C] = 0, [A, B] \neq 0.$$

A necessary assumption, in order to avoid contradictions, is that the observables A and C may be measured in the same experiment and similarly for B and C , but A and B cannot be measured with the same experimental arrangement. (It is usual to speak about simultaneous measurements although it is not a question of same time but of same experiment. However the common language will be used here). With repeated measurements in identical experiments it is possible to obtain the joint probability distribution for the results of the the former measurement, which I will represent by the density, $\rho(a, c)$, that the observable A takes the value a , and the observable C the value c . Similarly we may obtain $\rho(b, c)$, but it is not possible to obtain a joint probability density $\rho(a, b)$ because we cannot measure A and B simultaneously. Up to here no problem arises, everything is consistent.

Now if we think that the measurement just reveals preexisting values of the observable quantities we are compelled to assume that in every state the

system possesses the values a, b and c , independently of any observation or measurement. More generally the preparation procedure will lead to a joint probability distribution, $\rho(a, b, c)$, for the three observables. If this is the case the joint probabilities for two observables should be the marginals of the former distribution, that is

$$\rho(a, c) = \int \rho(a, b, c) db, \quad \rho(b, c) = \int \rho(a, b, c) da. \quad (13)$$

However there are particular cases of states and observables where no (positive) joint probability density $\rho(a, b, c)$ exists such that the marginals eq.(13) agree with the quantum prediction. This is the essential content of the Kochen-Specker theorem already mentioned in the previous section. It has been discussed in many places[24], [3]. The conclusion seems unavoidable: *we cannot assume that physical systems possess properties independently of measurements.*

Does that assumption prevents a realistic interpretation of quantum physics?. I think not. Firstly I point out that a similar situation may happen in classical physics, although certainly is not common. This is the case when we play dice. If we get a number, say 2, we cannot say that the value 2 was preexistent to our experiment of throwing the dice. In fact the result 2 is actually “created” by the experiment. Returning to quantum physics, there is a simple explanation for the inexistence of properties independent of measurements (in general, because some particular properties do exist, for instance the mass). We shall assume that the measured properties are *contextual*, that is they depend not only on the state of the system but on the whole experimental context. This point was correctly emphasized by Bohr and, in my opinion, solves all the problems of interpretation which might follow from the Kochen-Specker theorem.

The real difficulty arises when people attempts to reach conclusions which go well beyond what follows from the facts. Indeed we can state that *some properties* do not exist independently of measurements *in some particular instances*, but we should not extrapolate telling that in nature *there are no properties* independent of the observation. This absurd extrapolation was correctly criticized by Einstein with his celebrated rhetorical question “*Is the moon there when nobody looks?*”[11].

One might ask why in the microscopic domain it is very frequent that values of the observables are created by the experiments whilst this situation is rare in the macroscopic world. An explanation may be as follows. In the

macroscopic world we may study systems with instruments more fine than the object to be studied. E. g. we may look at the interior of an orange using a knife. In the microscopic domain any equipment used for the study of atoms will consist of atoms. This makes our knowledge less direct in the micro than in the macroscopic domain, and more dependent on the context.

4.4 The theory of measurement

In the most popular interpretation of quantum mechanics at present, the many worlds MWI, there is no theory of measurement. Thus the discussion in this subsection is somewhat out of date, but due to its relevance during almost half a century of hegemony of the Copenhagen interpretation (actually MCI) it may be appropriate to devote a subsection to the subject.

In MCI it is assumed that quantum mechanics requires, in addition to the formalism, a theory of measurement. The existence of a “theory of measurement” is peculiar, it does not exist in any other theory in physics (or, more generally in natural science). It is true that from a philosophical (epistemological) point of view any theory requires some assumptions for the connection with the results of observations or experiments. For instance in classical mechanics we use the concepts of time, space, particle, isolated system, etc., and there are “semantical” rules telling us how these concepts should be related to the (mathematical) formalism.

The mere existence of a theory of measurement has been strongly criticized by philosophers of science like Karl Popper[28] or Mario Bunge. In particular the latter[6] stresses that a physical theory should not include a *general theory of measurement*, but particular recipes or protocols for every specific measurement. This is most clear in chemistry. There are *recipes* for the preparation of, say, pure alcohol, or *protocols* for analysing the water of a river. However it would be absurd to search for a “general theory of preparation or analysis” in chemistry. In my opinion the same is true in physics, including quantum physics.

There were two reasons for introducing a theory of measurement in quantum mechanics: 1) If we do not believe in the existence of objective properties independent of measurement, we need a rule connecting an element of the formalism (a self-adjoint operator) with the result of the measurement (the value of an observable). 2) The theory of measurement apparently solves the problem of objectification or individuation mentioned above.

In my opinion the correct solution is not the theory of measurement but

to assume that: 1) The values of the observables measured are contextual, they depend on both some objective properties of the microscopic systems (usually not directly observable) and the whole experimental context. 2) The wavefunction (or statevector) of a so-called pure (quantum) state should be interpreted as belonging to a statistical ensemble. This is the ensemble interpretation[1], advocated by Einstein[10].

In summary, a measurement theory is absurd from the epistemological (philosophical) point of view, and unnecessary from the physical side.

4.5 Probabilistic character

The current wisdom is that quantum probabilities are radically different from the classical, ordinary life, probabilities. The latter derive from ignorance (incomplete knowledge), maybe unavoidable, about the truth of some assertion. For instance we may attach a probability $1/2$ to the appearance of head in throwing a coin, but we are convinced that if we were able to control all relevant variables in the experiment we could predict the result with certainty. In contrast it is assumed that quantum probabilities are quite different, that they derive from a lack of strict causality of the natural laws, that is the fact that different effects may follow to the same cause. This is usually called the *fundamental or essential probabilistic* character of the physical laws.

Einstein disliked that assumption and strongly criticized it, as shown with his celebrated sentence “*God does not play dice*”. I understand very well Einstein’s opinion. For him the rational understanding of nature was a kind of religion. As more loose (strict) are the natural laws smaller (greater) could be our rational understanding of nature. Accepting a weak causality is like accepting weak science. However there are people happy with the absence of determinism implied by the nonexistence of strict causality. For instance some people claim that the quantum lack of determinism may explain human freedom. In any case this question lies outside the scope of this paper and I will not comment further on it.

In my opinion quantum mechanics is a stochastic theory. There are strictly causal laws, but there is also an universal noise, in the form of vacuum fluctuations, which permeates everything and prevents any practical determinism in the evolution. Strict causality combined with stochasticity (randomness) is in practice indistinguishable from essential probability, and the former is for me more plausible. Again the belief in essentially probabilistic laws derives from the persistent belief that quantum mechanics is

complete. In contrast an ensemble interpretation of the wavefunction leads naturally to the appearance of probabilities.

4.6 Wave-particle duality

The assumption that all entities have a dual nature, particle and wave, is the source of most difficulties for an intuitive understanding of quantum mechanics. If we do not want to destroy the basic properties of space, the wave-particle duality really involves a contradiction. In fact *particle* means something localized, *wave* something extended. In both cases in comparison with the typical size of devices used for the experiment. In my opinion it is absurd to say that an atom passes by two slits at the same time, an assertion frequent in the literature. Thus it is not strange that Feynman said that the interference experiments contain all the mysteries of quantum mechanics.

I think that the electrons (or protons, neutrons, atoms, molecules) are particles, whilst radiation consists of waves. “Photons” are not particles but mathematical constructs useful for the description of some phenomena[18]. Then, how may we interpret the interference experiments where we observe fringes typical of waves, but these fringes appear as sets of localized events which are typical of particles? In the case of radiation the interference may be easily understood in classical terms, the problem is the particle behaviour in the detection. The opposite is true for particles like atoms. Its localized detection is easy to understand but their interference puts a big problem. Let us study the two cases separately.

The detection of individual photons in a photographic plate is due to the atomic nature of the plate. In this case saying that radiation are particles because they give rise to individual blackened grains is like saying that wind is corpuscular because the number of trees falling in the forest is an integer. Of course in both cases, the photo and the forest, there is a random element. It is obvious for the wind but, as explained above, there is also a random element in the radiation: the quantum noise.

The detection process in a photon counter may be explained as follows. Inside the detector there are systems, like molecules, in a metastable state. The arriving radiation, with a random element due to the quantum (vacuum) noise, has from time to time sufficient intensity to stimulate the decay of the metastable system and this gives rise to a photocount. However the noise alone, being fluctuating, may eventually produce counts in the absence of any signal, which are called dark counts. (Dark counts are usually attributed

to thermal fluctuations, but I claim that quantum fluctuations may produce them also.) The counter behaves like an alarm system. If it has low sensitivity it may not detect some relevant perturbation, but if it is too sensitive it may be activated by accident. The same is likely true for photon counters. This leads me to conjecture that it is not possible to manufacture detectors with 100% efficiency but no dark counts and that trade-off is the origin of the so-called efficiency loophole in the optical tests of Bell's inequalities.

The wave behaviour of neutrons, atoms or molecules, for instance the apparent interference in two-slits experiments, is more difficult to understand. We might assume that space is filled with the quantum noise, consisting of a random electromagnetic radiation, fluctuations of the spacetime metric and possibly other components. That noise is what interferes, producing a pattern which guides the particles. The picture has some similarity with the old proposal by L. de Broglie (the pilot wave theory) or the picture offered by "Bohmian mechanics" [4], but there are two important differences. Firstly in our model there is a clear physical entity different from the particles which interferes, namely the vacuum fluctuations (or quantum noise), whilst the particle remains localized all the time. Secondly there is a random element which is not present in Bohmian mechanics.

5 How to get a physical model from the formalism

In spite of the difficulties above commented, I conjecture that it is possible to reach a physical model of the quantum world. Indeed I am convinced that an intuitive understanding of quantum mechanics is possible provided one accepts the following:

Proposition 1 *The difficulties for getting a clear and coherent world view of quantum physics lie in either: 1) alleged predictions which actually derive from a wrong application of the quantum formalism, or 2) alleged predictions following from too simplified models of actual experiments which neglect relevant quantum corrections.*

In the following I clarify the point with an example of each kind.

5.1 Cosmic delayed choice experiment

Predictions derived from a wrong use of the formalism happen in the popular presentation by J. A. Wheeler of the “delayed choice experiment”[36]. The hypothetical experiment consists of detecting light coming from a distant quasar. It is assumed that it emits photons which, in the travel to Earth, encounter a galaxy which produces a lensing effect, so that the photons may arrive at our laboratory via two different routes. Thus we may either detect interference or directly detect the photons in one of the beams. The mind boggling conclusion is that the results of the experiment seem to imply that every photon should choose whether to pass via only one of the possible paths around the galaxy or to travel via both paths in order to produce interference. And the photon should decide what to do anticipating our choice, to be made millions of years later. It is certainly difficult to understand this behaviour, but the fact is that the experiment actually realizable is very easy to understand. “Photons are the quanta of light, but they are not particles” (Willis Lamb[18]). The light emitted by the distant quasar is thermal (chaotic) which has a completely different representation than single photons signals, a fact known to every quantum optician. Chaotic light remains chaotic light no matter how weakened, so that the said experiment will never show interference. Of course, a kind of delayed choice experiment (involving photon interference and anticorrelation after a beam splitter) has been performed in the laboratory[16], but it required the existence of two correlated (entangled) light beams. Actually that experiment may be intuitively understood without difficulty, as I have shown elsewhere[21].

5.2 Tests of Bell inequalities

A current wisdom is that many experiments have violated Bell inequalities and therefore local hidden variables are impossible (which is usually stated saying that local realism has been refuted), a belief which is not true. In the following I comment on Bell tests as an example of the difference which exists between the prediction of quantum mechanics for an ideal (simplified in excess) model of an experiment and the prediction for a realizable experiment.

An ideal experimental test of Bell’s inequality may consist of preparing two spin 1/2 particles (say silver atoms) in the singlet spin state, placing the particles at some distance from each other and measuring the correlation of the spin projections on two different directions (say forming angles ϕ_A and

ϕ_B with a vertical plane which contain the two particles). The quantum prediction for the correlation (as defined in section 2, see paragraph above eq.(10)) is

$$\langle AB \rangle = \frac{1}{2} [1 + \cos(\phi_A - \phi_B)]. \quad (14)$$

We should perform the measurements (in different runs of the experiment) with four different positions of the spin analyzers. Thus it is easy to check that the choice

$$\phi_{A1} = 0, \phi_{B1} = \pi/4, \phi_{A2} = \pi/2, \phi_{B2} = 3\pi/4, \quad (15)$$

leads to

$$\langle A_1 B_1 \rangle = \langle A_1 B_1 \rangle = \langle A_1 B_1 \rangle = \frac{1}{2} + \frac{\sqrt{2}}{4}, \langle A_2 B_2 \rangle = \frac{1}{2} - \frac{\sqrt{2}}{4}, \quad (16)$$

which violates the Bell inequality (10).

This looks very simple, but it is the case that an actual experiment of the kind described would be extremely complex or else the quantum predictions would not predict a violation of the Bell inequality. The reader may look at the extremely complex proposal, published by Fry et al. in 1995[14], of an allegedly realizable experiment which nevertheless has never been performed. Indeed no (loophole-free) experimental test of a Bell inequality has been so far made, in almost 50 years elapsed after Bell's work. The prejudices against hidden variables (or the possible incompleteness of quantum mechanics) has lead to a strong opposition to admit that no experiment has actually violated local realism. This fact is currently disguised with the statement that "local realism has been violated modulo some (supposedly irrelevant) loopholes". Most of the experiments performed have used either optical photons or atoms[31], [32]. For the former the problem is the *detection loophole*, for the latter *the locality loophole*. In the following I comment separately on both.

In experiments with photons, performing the measurements at spacelike separation is not too difficult, the problem is the low efficiency of the available (optical) photon counters. The reason for that may be traced back to the wave-particle complementarity. Photons are not point particles, but objects with a size of order the wavelength. Polarization is a wave property whilst detection might be considered a particle behaviour. High energy photons (say gamma rays) have a small wavelength (and thus an atomic or subatomic

size) and consequently its particle behaviour is dominant. They may be detected with good efficiency via devices consisting of atoms. However the measurement of their polarization involves a somewhat large uncertainty. Thus no experiment involving pairs of gamma rays (e. g. produced in the positronium decay) might show a violation of a Bell inequality.

The opposite is true for optical photons. There are very efficient polarizers but the detection is uncertain. As I said in section 2, photon counters are similar to alarm systems: if the detection efficiency is high, the rate of accidental counts is also high or the detection probability ceases to be linear in the intensity. If for simplicity we assume a linear detection probability and label η the detection efficiency and ε the noise to signal ratio, that is the ratio between dark counts and true photon detections, eq.(14) becomes

$$\langle AB \rangle = 1 - \eta(1 + \varepsilon) + \eta^2 [1 + \cos(2\phi_A - 2\phi_B)], \quad (17)$$

where I have neglected the noise in the coincidence detection (false coincident counts). A factor 2 in the angles derives from the spin 1, rather than 1/2, of the photons. If we insert the result in the Bell inequality (10) we get

$$|\langle A_1 B_1 \rangle + \langle A_2 B_1 \rangle + \langle A_2 B_2 \rangle - \langle A_1 B_2 \rangle| \leq \left| 2 - 2\eta(1 + \varepsilon) + \eta^2 [1 + \sqrt{2}] \right| \leq 2, \quad (18)$$

where I have taken into account that the left hand side achieves the maximal value if we choose the angles to be half those of eq.(15). Therefore the Bell inequality is fulfilled whenever the following inequality holds true

$$\eta < 0.82(1 + \varepsilon),$$

which has been the case in all performed experiments. It is claimed that the Bell inequality would be violated if we extrapolate the empirical result eq.(18) to the ideal case $\varepsilon = 0$, $\eta = 1$, which is named *faithful sampling assumption*. It may be realized that this hypothesis is equivalent to assuming that hidden variables do not exist, but I shall not discuss this point in more detail here. I finish stressing that *the results of experiments with optical photons do not show a real violation of a Bell inequality*. Only the extrapolation of the actual results to a hypothetical *ideal experiment* would produce a violation.

In experiments with atoms the detection may be quite efficient and the property corresponding to the polarization of photons (i. e. a linear combination of different atomic states) has been also measured with good efficiency in the experiment by Rowe et al.[29]. Thus the Bell inequality (10) has been

violated. As a consequence *the experiment has refuted non-contextual hidden variables theories* (see section 2 for the proof that the violation of a Bell inequality refutes non-contextual HV theories). However the measurements have not been made insuring spacelike separation, and therefore local HV theories have not been refuted. (The politically correct form of the latter statement is to say that “local hidden variables theories have been refuted by the experiment, modulo the locality loophole”.)

As a summary of the subsection I repeat my old conjecture[31]: *Local realism is compatible with quantum mechanics*, provided that we call quantum predictions only those for real experiments, that is we exclude “predictions” for ideal, unrealizable, experiments.

6 Conclusions

Amongst the current interpretations of quantum mechanics the many worlds (MWI) is the only one which does not require additional assumptions. It follows rigorously from the universal validity of quantum mechanics. However in order to avoid a Platonic paradigm (see subsection 3.3), strange to natural science, it should be combined with an ensemble interpretation (EI), so giving rise to an interpretation which is realistic and not bizarre. However the problem of finding a physical model of the world remains open.

A realistic interpretation giving rise to a physical model of the world, would make quantum mechanics more palatable to lovers of *theory*, in the ethimological sense of contemplation. It would allow “understanding quantum mechanics”, in the sense of Feynman’s dictum quoted at the beginning of this paper. Reaching such a model is extremely difficult as I have commented in this article, mainly due to spurious additions to the quantum formalism, which have become a part of the current quantum paradigm. I am convinced that getting a model is possible provided that we consider only actual predictions of quantum mechanics, that is we exclude predictions for ideal experiments that involve undue simplifications.

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